

A New Giant Branch Clump Structure In the Large Magellanic Cloud

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Received _____; accepted _____

To be submitted to the Astronomical Journal

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ABSTRACT

We present Washington C, T_1 CCD photometry of 21 fields located in the northern part of the Large Magellanic Cloud (LMC), and spread over a region of more than 2.5° approximately 6° from the bar. The surveyed areas were chosen on the basis of their proximity to SL 388 and SL 509, whose fields showed the presence of a secondary giant clump, observationally detected by Bica et al. (1998, AJ, 116, 723). We also observed NGC 2209, located $\sim 14^\circ$ away from SL 509. From the collected data we found that most of the observed field CMDs do not show a separate secondary clump, but rather a continuous vertical structure (VS), which is clearly seen for the first time. The VS also appears in the field of NGC 2209. Its position and size are nearly the same throughout the surveyed regions: it lies below the Red Giant Clump (RGC) and extends from the bottom of the RGC to ~ 0.45 mag fainter, spanning the bluest color range of the RGC. In two fields as well as in the NGC 2209 field, the RGC is slightly tilted, following approximately the reddening vector, while the VS maintains its verticality. We found that the number of stars in the VS box defined by $\Delta(C - T_1) = 1.45\text{--}1.55$ mag and $\Delta T_1 = 18.75\text{--}19.15$ mag has a strong spatial variation, reaching the highest VS star density just north-east of SL 509. Moreover, the more numerous the VS stars in a field, the larger the number of LMC giants in the same zone. We also found that, in addition to SL 509, two relatively massive star clusters, SL 515 and NGC 2209, separated by more than ten degrees from each other, develop giant clumps with a considerable number of VS stars. This result demonstrates that VS stars belong to the LMC and are most likely the result of some kind of evolutionary process in the LMC, particularly in those LMC regions with a noticeable large giant population. Our results are successfully predicted by the models of Girardi (1999, MNRAS, submitted) in the sense that a large proportion of 1-2 Gyr old stars mixed with older stars, and with metallicities

higher than $[\text{Fe}/\text{H}] \simeq -0.7$ should result in a fainter and bluer secondary clump near the mass where degenerate core He burning takes place. However, our results apparently suggest that in order to trigger the formation of VS stars, there should be other conditions besides the appropriate age, metallicity, and the necessary red giant star density. Indeed, stars satisfying the requisites mentioned above are commonly found throughout the LMC, but the VS phenomenon is only clearly seen in some isolated regions. Finally, the fact that clump stars have an intrinsic luminosity dispersion further constrains the use of the clump magnitude as a reliable distance indicator.

keywords : galaxies: individual (Magellanic Cluds) — galaxies: photometry —
galaxies: stellar content

1. INTRODUCTION

The Large Magellanic Cloud (LMC) has long been a favorite stellar laboratory, providing us not only with valuable information about its own complex star formation history but also with important clues for understanding the formation and evolution of distant galaxies. Moreover, the interest in studying different astrophysical aspects of this galaxy has been rapidly increasing recently, mainly due to the advent of more powerful telescope/instrument combinations and computing facilities.

Recently, Geisler et al. (1997, hereinafter Paper I) carried out a search for the oldest star clusters in the LMC by observing with the Washington C, T_1 filters candidate old clusters spread throughout the LMC disk. Although they did not find any genuine old cluster like the Galactic globular clusters, their study has considerably increased the sample of intermediate-age clusters ($t \sim 1\text{-}3$ Gyr) with ages determined with a high degree of confidence. In addition, their results reinforce the conclusion that an important epoch of cluster formation, which began ~ 3 Gyr ago, must have been preceded by a quiescent period of many billion years, unless dissipation processes have been more effective than previously thought (e.g., Olszewski 1993). In addition, they determined not only the properties of the clusters but also those of their surrounding fields. From the relatively wide field covered by their images ($\sim 15'$ on a side) they found that clusters and fields have on average similar ages and metallicities, except in 3 cases where clusters are ≈ 0.3 dex more metal-poor than the surrounding field, suggesting that the chemical evolution was not globally homogeneous (Bica et al. 1998, hereinafter Paper II).

A further intriguing result of Paper II was the discovery of what appeared to be a well populated secondary clump in the Color-Magnitude Diagrams (CMDs) of two fields located in the northern part of the LMC near the clusters SL 388 and SL 509. This unusual feature, made up by stars distributed uniformly across the fields, lies below the prominent Red Giant

Clump (RGC) slightly toward its bluest color and extends 0.45 mag fainter. The feature also appears in the very populous SL 769 field located $\sim 6^\circ$ away, thus representing around 10% of the whole sample of fields observed in Paper I. Since this feature appeared as a roughly distinct secondary clump, Bica et al. coined the term “dual clump” to describe this phenomenon. The authors tentatively suggested that these stars are evidence of a depth effect with a secondary component located behind the LMC disk at a distance comparable to the Small Magellanic Cloud (SMC), perhaps due to debris from previous interactions of the LMC with the Galaxy and/or the SMC. However, they also mentioned arguments against this scenario and noted other possible explanations.

Westerlund et al. (1998) have also found a similar feature in the CMDs of three fields located in the NE of the LMC. On the basis of their BV photometry they suggested that the red giant clump is bimodal and contains stars from an old population ($t \geq 10$ Gyr) and from another younger population ($t \geq 0.3\text{--}4$ Gyr), in the sense that the fainter the clump the older the stars. Besides observational findings, Girardi et al. (1998) and Girardi (1999) have theoretically predicted that stars slightly heavier than the maximum mass for developing degenerate He cores should define a secondary clumpy structure, about 0.3–0.4 mag in the I band below the bluest extremity of the red clump. According to Girardi (1999) this evolutionary effect should be seen in CMDs of composite stellar populations containing ~ 1 Gyr old stars and with mean metallicities higher than $Z = 0.004$. However, the current state of both observational and theoretical results makes it impossible to determine whether the intriguing feature is caused by the presence of an old stellar population or by an evolutionary effect or even by a layer of stars located behind the LMC. Furthermore, not only its origin but also its morphology remains uncertain, which must be known before the magnitude of the red giant clump can be used as a robust distance indicator (e.g., Paczyński & Stanek 1998).

In this paper we report on the first observations carried out with the aim of mapping the extent and determining the nature of the “dual clump” phenomenon. Indeed, the apparent dual clumps from the limited sample of Paper II are now found to merge and form a continuous feature. The selection and observation of the fields, as well as the reduction of the data are presented in Section 2. In Section 3 we present the results and discuss them in the light of recent theoretical and observational interpretations. Finally, in Section 4 we summarize our main conclusions.

2. OBSERVATIONS AND REDUCTIONS

The fields for mapping out the extent of the secondary clump phenomenon were selected on the basis of their proximity to SL 388 and SL 509, and the presence of star clusters which had not been observed with Washington photometry. The first criterion aims at observing LMC regions located not only in the line of sight between SL 388 and SL 509, but also those placed around them within one degree from the midpoint of both clusters. The nearest cluster from this center from Paper II is SL 262 which is located 1.5° from SL 388 and no dual clump structure is visible in its CMD. In order to maximize the assigned telescope time, we centered the fields so that they included clusters without, or with only very unreliable, age and metallicity determinations for our continuing study of the chemical evolution of the LMC. The clusters having integrated *UBV* photometry were taken from Bica et al. (1996), and the fainter ones from the recent revised catalog of star clusters, associations and emission nebulae (Bica et al. 1999). We also observed the field of NGC 2209 for the purpose of checking the possible evolutionary origin of the dual clump. This cluster is located $\sim 14^\circ$ toward the south-east from SL 509 and placed by Corsi et al. (1994) photometric data in the minimum of the relationship between red giant clump and Main Sequence (MS) termination magnitudes. Table 1 lists the selected fields and the

clusters contained within these fields. Note that fields # 5, 16, 17, 23, and 26 were not observed.

The observations were carried out at the CTIO 0.9m telescope during 6 photometric nights in November 1998. The Cassegrain Focus IMager (CFIM) and the CCD Tek2K #3 were employed in combination with the Washington C and Kron-Cousins R filters. Geisler (1996) has shown that the R_{KC} filter is a very efficient and accurate substitute for the Washington T_1 filter. The pixel size of the detector was $0.4''/\text{pixel}$, resulting in a field of $\sim 13.5'$ wide. We used the Arcon 3.3 data acquisition system in *quad* mode (four amplifiers) with a mean gain and readout noise of $1.5 e^-/\text{ADU}$ and $4.2e^-$, respectively. During each night exposures of 2400^s in C and 900^s in R_{KC} were taken for the selected fields as well as for standard fields (Geisler 1996) with airmasses approximately ranging from 1.1 up to 1.6. In addition, a series of 10 bias and 5 dome and sky flatfield exposures per filter were obtained nightly. The weather conditions kept very stable with a typical seeing of $1.0''$ - $1.2''$, although some images have slightly larger FWHMs due to temperature changes of up to 2° C. In general, the secondary mirror was focused twice per night. We covered a total area of $\approx 1^\square$ spread over $\sim 2.6^\square$.

The collected data for a total of 21 selected fields and the NGC 2209 field were fully processed at the telescope using the QUADPROC package in IRAF³. The distribution of the observed fields is shown in Fig. 1. After applying the overscan-bias subtraction for the four amplifiers independently, we carried out flatfield corrections using a combined skyflat frame, which was previously checked for non-uniform illumination pattern with the averaged domeflat frame. Then, we did aperture photometry for the standard fields

³IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

(~ 30 stars per night) using the PHOT task within DAOPHOT II (Stetson 1991). The relationships between instrumental and standard magnitudes were obtained by fitting the following equations :

$$c = a_1 + C + a_2 \times X_C + a_3 \times (C - T_1) \quad (1)$$

$$r = b_1 + T_1 + b_2 \times X_R + b_3 \times (C - T_1), \quad (2)$$

in which a_i and b_i ($i = 1, 2$ and 3) are the coefficients derived through the FITPARAM routine in IRAF, and X represents the effective airmass. Capital and lowercase letters represent standard and instrumental magnitudes. The resulting coefficients and their standard deviations are listed in Table 2, the typical rms errors of eqs. (1) and (2) being 0.017 and 0.015 mag, respectively.

Point Spread Function (PSF) photometry for the LMC fields and the NGC 2209 field was performed using the stand-alone version of the DAOPHOT II package (Stetson 1994), which provided us with X and Y coordinates and instrumental c and r magnitudes for all the stars identified in each field. The PSFs were generated from two samples of 30-35 and ~ 100 stars selected interactively. For each frame a quadratically varying PSF was derived by fitting the stars in the larger sample, once their neighbors were eliminated using a preliminary PSF obtained from the smaller star sample, which contained the brightest, least contaminated stars. Then, we used the ALLSTAR program for applying the resulting PSF to the identified stellar objects and creating a subtracted image which was used for finding and measuring magnitudes of additional fainter stars. The PSF magnitudes were determined using as zero points the aperture magnitudes yielded by PHOT. This procedure was iterated three times on each frame. Next, we computed aperture corrections from the comparison of PSF and aperture magnitudes using the subtracted neighbors PSF star

sample, resulting in typical values around -0.016 ± 0.010 mag. Notice that PSF stars are distributed throughout the whole CCD frame, so that variations of the aperture correction should be negligible. Finally, the standard magnitudes and colors for all the measured stars were computed inverting eqs. (1) and (2), once positions and instrumental c and r magnitudes of stars in the same field were matched using Stetson’s DAOMATCH and DAOMASTER programs. Thus, we achieved accurate photometry for $\sim 242,000$ stars, with mean magnitude and color errors for stars brighter than $V = 19$ of $\sigma(T_1) = 0.014$ and $\sigma(C - T_1) = 0.022$ mag, respectively.

Later on, with the aim of gathering both astrometric and photometric information in a self-consistent way, we built a master file which contains the positions for all the stars referred to a unique coordinate system. For some fields we only applied the appropriate offsets in the X and Y values, while in other fields we matched from tens up to hundreds of stars in common using DAOMASTER and our own routines. We also averaged their T_1 magnitudes and $C - T_1$ colors and recomputed their photometric errors based on the difference. The typical mean difference (absolute value) for approximately five hundred stars brighter than $V = 19$ in common turned out to be $\Delta T_1 = 0.026 \pm 0.021$ and $\Delta(C - T_1) = 0.030 \pm 0.023$. In total, 7760 stars have two measurements of their magnitude and color. This photometry can be obtained from the first author upon request.

3. ANALYSIS AND DISCUSSION

3.1. Description of CMDs

The CMDs of the 21 observed LMC fields certainly show a mixture of different stellar populations. They appear to be dominated by a 3-4 Gyr old population as deduced from the δT_1 index, which measures the difference in magnitude between the mean magnitude

of the clump/HB and the MS turnoff (see Paper I). Fig. 2 illustrates a typical field CMD of the surveyed region. Likewise the MS is well-populated and extends along ~ 3 mag. Assuming that the MS comes from the superposition of MSs with different turnoffs, we estimated an age range from 3 up to 7.5 Gyrs using the δT_1 index, with an average of 4.5 ± 1.0 Gyr for all the fields. This significant age range is also supported by the presence of a Sub Giant Branch (SGB) with a broad vertical extension due to the transition of MS stars with different ages to the SGB. The Red Giant Branch (RGB) is also clearly visible covering a wide range in color from $C - T_1 \sim 1.8$ up to 3.6. However, the most striking feature of these CMDs is the giant clump region. In addition to the normal Red Giant Clump (RGC), most of the field CMDs also show a vertical structure (VS) composed of stars which lie below the RGC and extend from the bottom of the RGC to ~ 0.45 mag fainter. The VS spans the bluest color range of the RGC and also appears in the CMD of NGC 2209. This intriguing feature does not clearly appear in the CMDs of our previous LMC clusters survey, but only a dual clumpy structure in around 10% of the cluster sample (see Paper II). To our knowledge, such a feature has not been observed previously.

In order to delimit and characterize this intriguing feature, we first estimated its position and size, and examined its shape going through the individual field CMDs. An enlargement of the area of interest in these CMDs is shown in Fig. 3. As can be seen, the RGCs are nearly located at the same magnitude and color, centered at ≈ 18.5 and 1.60 mag, respectively. The constancy of the location in the CMD also appears to be the case for the VS, even in those fields where the VS arises as a small and sparse groups of stars. In two fields (marked with an asterisk in Fig. 1) the RGC is slightly tilted, following approximately the reddening vector, but the mean positions of both the RGC and VS remain unchanged. Moreover, the VS maintains not only its mean position but also its verticality. Therefore, given that the locus of the VS in the CMD does not seem to show any correlation with position in the LMC and that reddening variations over our survey field should be minimal

and, in order to highlight the VS phenomenon, we built a composite CMD using all the measured stars. The resulting diagram is shown in Fig. 4 in which we also included our published Washington photometry for SL 338 and SL 509 (see Section 3.2). We define VS stars as those stars which fall into the rectangle $T_1 = 18.75$ -19.15 and $C - T_1 = 1.45$ -1.55. This definition results in a compromise between maximizing the number of VS stars and minimizing contamination from, among other sources, MS, SGB, RGB, and Red Horizontal Branch stars. The continuous nature of this feature is clearly evident. We are unsure of the reason why this feature appeared as a “dual clump” in two of our Paper II fields. In none of our present fields is there any significant bifurcation. The composite CMD of Fig. 4 thus should present the best representation of this feature.

3.2. The VS phenomenon

It was mentioned above that VS stars appear to be present in most of the fields of Fig. 1, although in some of them they could hardly be recognized. Therefore, it would be appropriate to map out the extent of the VS phenomenon in order to have a more quantitative estimate of its dimensions. For that purpose, we counted the number of stars lying within the VS rectangle, assuming for all the fields the same Galactic field star distribution. This assumption is particularly true if the CMDs of cluster fields located in different parts of the LMC disk (see Fig. 4 in Paper II) are compared with that of the outermost field (OHSC 37), for which we found no evidence of LMC field stars (see Santos et al. 1999, hereinafter Paper III). Furthermore, in an area of the same size as the selected LMC fields, the OHSC 37 field only has two stars within the VS box, so that we did not perform any correction due to foreground star contamination. The number of stars we counted for the northern LMC fields are shown in Fig. 1. The VS stars show a **strong spatial variation**, reaching their highest density just north-east of SL 509.

We also repeated the same counting procedure for the fields of SL 126, SL 262, SL 388, SL 509 and SL 842 by revisiting our Washington data published in Paper II. SL 126, SL 262 and SL 842 are the nearest clusters to SL 388 and SL 509. Both present and published data sets were obtained following the same stellar object selection criteria, so that they can be compared directly. The number of VS stars in SL 388 and SL 509 is 37 and 106, which successfully match the trend followed by the selected LMC fields (see Fig. 1). On the other hand, the fields of SL 126, SL 262 and SL 842 turned out to have 4, 9 and 9 VS stars, respectively, placing an upper limit to the size of the VS region. All these results suggest that the region in which the VS phenomenon is concentrated extends over at least $\sim 2^\circ$ and that the feature is not clearly seen either in the field of SL 262, which is $\sim 1.5^\circ$ to the NW of SL 388, nor in SL 842 located $\sim 4.5^\circ$ to the NE of SL 509.

With the aim of looking into whether VS stars are also found in LMC **clusters**, we took advantage of the fact that there is roughly one star cluster in each selected field; the total cluster sample being 21. First, we determined the cluster centers and selected their radii by eye-judging the variation of the stellar density in the cluster surroundings. Cluster radii vary between 20 and 110 pixels with an average of 45 pixels ($20''$). Then, we performed VS star counts within both cluster radii and four circular LMC field areas on the same image chosen for comparison purposes. The four circular field areas were distributed throughout the entire image; none of them closer to the corresponding cluster than three cluster radii, thus avoiding cluster star contamination. They were also located far away from the image edges, avoiding vignetting and flatfield residuals effects. Finally, the radii of the four comparison areas in each image were fixed at one-half of the cluster radius. Eighty percent of the selected LMC comparison fields contained no VS stars, while one and two VS stars were found in two and one LMC comparison fields, respectively. These results are in very good agreement with the total number of VS stars found in each frame once they are scaled to the cluster area. Similarly, star clusters apparently also have no VS stars, except

in the case of SL 515 which has 12 VS stars, five of them lying inside $1/2$ of the cluster radius ($r \sim 45''$). SL 515 is located in one of the selected LMC fields with the highest VS star densities as can be seen in Fig. 1. However, $9'$ to the SE from SL 515 there is another star cluster (SL 529) which only has two VS stars. Therefore, the excess of VS stars in SL 515 would not seem to be related to the peak in the field VS star distribution, but with some property of the cluster itself, presumably its mass (see Section 3.3). By looking at the images and comparing the cluster radii we found that SL 515 is the largest and perhaps the most massive cluster in the sample. We also made the same comparison for the SL 388 and SL 509 fields and found one and five cluster VS stars, respectively, and no field VS stars. Both clusters have relatively large radii ($r \sim 30''$).

An additional test for exploring the nature of the VS phenomenon consists of comparing the number of VS stars with the total number of stars in the CMDs of different regions to investigate whether there is any trend of the ratio between them with their spatial distributions (No. VS stars/Total number CMD stars = $F(\text{position})$). For this test, we decided not to use the whole CMD of each selected LMC field because of different incompleteness factors at fainter magnitudes. Thus we did not consider MS stars but rather a box defined by $T_1 = 17.5\text{-}19.7$ and $C - T_1 = 1.0\text{-}2.2$, which are precisely the limits of the CMD in Fig. 4. This box (hereinafter RG box) includes all the red giant phases so that if there were any correlation between VS and LMC giant stars (strictly $\text{VS} = f(\text{RG-VS})$), it should arise without any bias due to the presence of MS or other kinds of stars. Fig. 5 shows the resulting relationship in which we also include the fields of SL 126, SL 262 and SL 842. There is a strong correlation between the number of VS stars in the field and the number of LMC giants in the same zone. The lowest VS star counts occur in the outermost LMC fields, such that of OHSC 37, where the number of red giants is also a minimum.

3.3. The NGC 2209 case

The giant clump luminosity is one of the best indicators of the development of the RGB, and consequently, an important tool for studying the nature of the VS phenomenon. Indeed, the RGC luminosity varies along a sequence which depends on the age (mass) of the giant stars. Furthermore, Corsi et al. (1994) data and Girardi (1999) models show that the clump magnitude (V_{clump}) has a maximum- (faintest value) as a function of the termination MS magnitude (V_{TAMS}) which corresponds to an age of ≈ 1.0 -1.5 Gyr. Precisely, our interest in observing NGC 2209 comes from the fact that this cluster falls onto the faintest magnitude in the V_{clump} vs. V_{TAMS} relationship shown in Corsi et al. (1994), thus providing us with a valuable opportunity to test whether the VS is caused by evolutionary effects. NGC 2209 is located $\sim 14^\circ$ away from the selected LMC fields and therefore any local effects in our VS area should be negligible.

Using our Washington photometry we performed an analysis similar to that carried out for the selected LMC fields, i.e., we first looked at the NGC 2209 field CMD. Its main features resemble those of the northern LMC fields, as shown in Fig. 6. The RGC is tilted and shifted with respect to Fig. 1 by $\Delta(C - T_1) \approx 0.20$ and $\Delta T_1 \approx 0.30$ mag. According to the relations $E(C - T_1) = 1.966E(B - V)$ and $A_{T_1} = 2.62E(B - V)$ (Geisler 1996) these offsets are consistent with a mean reddening ≈ 0.10 mag higher. Fig. 6 also reveals the presence of a VS at the same position relative to the RGC, reinforcing the conclusion that VS stars belong to the LMC. Its shape and magnitude extent are essentially the same as described in Section 3.1, while its color range is somewhat wider. The tilted RGC following approximately the reddening vector (see Fig. 6) could suggest the existence of differential reddening, although evolutionary effects could also yield an inclined clump. According to Catelan & Freitas Pacheco (1996) horizontal branch (HB) stars could result in a tilted clump if the helium content were very high ($Y=0.30$). They also argued that a differential

reddening as small as $\delta E(B - V) = 0.06$ mag cannot cause a CMD dispersion as large as the one originating from the evolution away from the Zero Age HB itself. Notice also that tilted clumps also appear in two fields marked with an asterisk in Fig. 1, but their positions and sizes (magnitude and color dispersions) are nearly the same as the remaining fields (see Section 3.1). On the other hand, Hodge (1960) noticed an apparently dark patch in NGC 2209 of $\sim 15''$ in diameter, about $10''$ from the cluster center, suggesting either an internal or foreground origin for the globule. In addition, using BV CCD photometry and CMD analysis, Dottori et al. (1987) concluded that the globule should be internal to the cluster, so that differential reddening is not unexpected. Indeed, we estimated a VS width approximately twice that of the northern selected fields. The extracted CMD of NGC 2209 also shows a remarkable color dispersion not only for giant clump stars, but also for SGB stars, which appear distributed at both edges of their whole color range (see Fig. 6).

Next, we counted the VS stars distributed in the NGC 2209 field using a box with the same dimensions as for the northern LMC fields and reddened by $\Delta E(B - V) = 0.10$. We also applied the same shift to the RG box, thus centering the RGC. The number of VS stars in the NGC 2209 field and in the cluster itself ($r \sim 45''$) was 69 and 10, respectively, whereas no VS stars were found in four circular field areas (equal cluster area criterion), as expected. This result is in very good agreement with that found for SL 515, in the sense that relatively massive clusters can develop giant clumps with a considerable number of VS stars. Finally, if we compare the field VS stars number with that corresponding to the RG box, we can conclude that LMC regions with a noticeable large giant population can also be reservoirs of VS stars. The fact that NGC 2209, located many degrees from our main VS area, also shows this feature argues against a depth effect interpretation (e.g., background galaxies or debris) and for an evolutionary origin.

3.4. Comparison with theory

It is known that stars defining the RGC in CMDs of intermediate-age and old open clusters are in the stage of central helium burning (Cannon 1970, Faulkner & Cannon 1973). However, according to Girardi (1999) models - computed using a grid of masses with a resolution of $\sim 0.1 M_{\odot}$ in the vicinity of the onset of helium burning mass - the position of GC stars in the CMD depends on the masses of the stars. Particularly, stars with $M \leq M_{He f} \sim 2 - 2.5 M_{\odot}$ form electron-degenerate cores with masses nearly constant ($M_c \simeq 0.45 M_{\odot}$) after the central hydrogen exhaustion, thus allowing stars to reach similar luminosities. These stars correspond to our RGC stars. On the other hand, for stars with $M > M_{He f}$ helium ignition takes place under non-degenerate conditions and both M_c and luminosity increase with $M_{He f}$, the minimum luminosity being about 0.4 mag fainter than those of stars with slightly lower masses. Girardi's models predict that such stars should define a secondary clumpy feature located below the RGC and at its bluest extremity, reminiscent of our VS feature. The spread in the intrinsic luminosity of stars burning helium in their cores evidenced by this feature provides a further constraint on using the magnitude of the GC stars as a self-consistent distance indicator.

Now, we can check Girardi's (1999) predictions in the light of the present observational findings, so that new constraints to the theory can improve our knowledge of stellar evolution and the star formation history in the LMC. In contrast with the tentative explanation of debris from a dwarf galaxy located behind the LMC suggested in Paper II, Girardi claimed that the secondary clump in the CMDs of SL 388 and SL 509 fields might have been caused by a population younger (higher mass) than RGC stars. However, in the present work we did not find such a separated fainter clump but rather a VS having approximately the same number of stars per magnitude interval and peaking at its brightest limit. The peak of the VS luminosity function has approximately 25% more stars than the remaining fainter

part of the VS, independent of the bin sizes (see Table 3 and Fig. 7). Therefore, the VS can be described as the faint tail of a long continuous vertical distribution formed by stars developing non-degenerate helium cores; the upper part of this long VS is represented by the so-called “vertical red clump” (VRC), recently extensively discussed in the literature (e.g., Zaritsky & Lin 1997; Beaulieu & Sacket 1998; Gallart 1998; Ibata et al. 1998). The presence of VRC stars in the Hess diagram (density-coded CMD) of a $2^\circ \times 1.5^\circ$ region located $\sim 2^\circ$ northwest of the center of the LMC was interpreted by Zaritsky & Lin (1997) as red clump stars that are closer to us than those in the LMC. However, according to Girardi et al. (1998) and Beaulieu & Sacket (1998), among others, evolutionary effects appear to describe its nature more satisfactorily. Thus, VRC stars should be the more massive clump stars, while stars with $M \sim 2 M_\odot$ should define the lower magnitude limit (Girardi’s secondary clump); stars with even smaller masses are grouped in the RGC. Fig. 4 shows the presence of not only VS stars but also VRC and HB stars. Note that even though both the Zaritsky & Lin and our present surveyed areas are roughly similar in size, VRC stars are clearly much less numerous than VS stars in our Fig. 4, which surprisingly contrasts with their Hess diagrams where no VS stars are seen despite the presence of the VRC. Certainly, if an LMC field contains both high mass (VRC) and low mass (RGC) stars, we should also expect to find intermediate-mass stars (VS stars), which were not detected in the Zaritsky & Lin survey data. We are uncertain as to what causes this paradox.

On the other hand, bearing in mind the differences mentioned above, it would be interesting to investigate how fundamental properties of VS stars compare with those predicted by Girardi for secondary clump stars. Note that Girardi predicted that secondary clumps should be observed in fields with an important number of 1 Gyr old stars ($M \sim 2 M_\odot$) mixed with older stars, and with metallicities higher than about $Z = 0.004$ ($[Fe/H] \simeq -0.7$). In addition, he pointed out that neither main nor secondary clumps should be mixed due to differential reddening, distance dispersions and photometric errors. We first derived

the ages of NGC 2209 and SL 515 and compared them with those of Girardi’s models. The cluster ages were estimated using the δT_1 index as defined in Paper I, yielding values of 1.5 and 1.6 Gyr for NGC 2209 and SL 515, respectively. These values are in good agreement with the ages associated with stars having $M_{He f}$ just in the limit for non-degenerate helium cores. We also estimated the ages for the remaining star clusters contained in the selected LMC fields, all of them resulting to be on average younger than 1.5 Gyr old. The ages derived for SL 388 and SL 509 in Paper II are 2.2 and 1.2 Gyr, so that slightly older stars than those predicted by Girardi’s models could also fall into the CMD VS region. However, most of the clusters and surrounding fields of Paper II - except ESO 121-SC03 - have ages in the range 1.0-2.2 Gyr, but only in two of them were secondary clumps clearly distinguished. Moreover, the metallicity of SL 509 is $[Fe/H] = -0.85$, while those of the surrounding cluster fields are all in the range $-0.35 - -0.7$.

In order to find some explanation for such a paradoxical result, which would appear to be opposite to the predictions of Girardi’s secondary clump models, we counted VS and RG box stars for all the surrounding fields of clusters analyzed in Paper II, and put these values in the VS vs. RG box plane. We applied reddening corrections with respect to the SL 388 and SL 509 fields ($E(B - V)=0.03$) and adopted the same foreground star contamination for all the fields, given the similar galactic star distribution in their CMDs compared to the field CMD of OHSC 37 (see Fig. 4 of Paper II). Fig. 5 shows the resulting relationship (open squares), in which we also included the 9 Gyr old field centered on ESO 121-SC03, the outermost OHSC 37 field, and the inner disk SL 769 field. In particular, the younger SL 769 fields turnoffs are younger than 1 Gyr, thus providing an important number of RG stars. As can be seen, fields with only a few RG box stars do not have many VS stars either, independent of their ages and metallicities, while VS stars become more important as the number of RG box stars increases. However, the surrounding fields do not seem to show the same correlation in Fig. 5 as for selected LMC fields (star symbols). In the case of

SL 769, the number of VS stars is near the average of those in the selected LMC fields, but RG box stars are nearly three times more numerous. Furthermore, the fields around SL 388 and SL 817 share similar ages, metallicities and number of VS stars, while the number of RG box stars in the SL 817 field is twice that in the SL 388 field, which suggests that a large number of RG stars alone is not a sufficient requirement for the appearance of the VS phenomenon. The number of VS stars in the fields of SL 509 and SL 862 are also quite different, although their ages, metallicities and number of RG box stars are very similar. Furthermore, SL 509 itself has 5 VS stars (see Section 3.2), whereas no VS stars appear to be associated with SL 862. All these results apparently suggest that there should be other conditions, besides age, metallicity and necessary RG star density, that would trigger the formation of VS stars, such as the environment of the VS star forming regions, different star formation rate, mass function, etc. Nevertheless, non-uniform spatial distribution of VS stars in the LMC reveals that non-homogeneously distributed star formation events occurred in this galaxy about 1-2 Gyrs ago.

4. CONCLUSIONS

From the analysis of Washington photometry for 21 selected fields located in the northern part of the LMC, and 14 cluster fields distributed throughout the LMC disk, we conclusively identify the existence of a vertical structure of stars that lies below the RGC at its bluest color and up to 0.45 mag fainter. Our previous data (Paper II) uncovered two northern fields which contained what appeared to be a “dual clump”, with a secondary clump lying fainter and bluer than the RGC. Stars lying in the same CMD region were described as very old stars ($t \sim 10$ Gyr) by Westerlund et al. (1998) from *BV* photometry of three fields located in the NE of the LMC. However, our much larger present database indicates that there exists a continuous distribution of stars, which we term VS (“vertical

structure”) stars, not only in the CMDs of field stars, but also in certain intermediate-age star clusters. These results demonstrate that VS stars belong to the LMC and that they are not composed of old objects in the LMC or of a background population of RGC stars. We also determine that VS stars are only found in those fields which satisfy some particular conditions, such as containing a significant number of 1-2 Gyr old stars and which have metallicities higher than $[\text{Fe}/\text{H}] \approx -0.9$ dex, in good agreement with Girardi’s (1999) models which predicted that a minimum in the luminosity of core He burning giants is reached just before degeneracy occurs. These conditions constrain the VS phenomenon to appear only in some isolated parts of the LMC, particularly those with a noticeable large giant population. However, a large number of RG stars, of the appropriate age and metallicity, is not a sufficient requisite for forming VS stars. Thus, for example, we found an area spread over 2.6° centered just to the north-east of SL 509 with 3 times fewer RG stars than the inner disk cluster SL 769, but with approximately the same number of VS stars. Clusters with the appropriate age and metallicity to contain a significant number of VS stars are also required to be relatively massive; NGC 2209, for example, constitutes a good example of Girardi’s predictions. Finally, although Girardi’s models successfully predict the existence of red giants fainter and bluer than RGC stars on the basis of an evolutionary effect, there is still a need for more detailed studies explaining for example the VS vs. RG relationship, the ratio between the number of VS and VRC stars, whether tilted RGCs are related with VS features, the VS luminosity function, etc. The fact that Zaritsky & Lin (1997) found red clump stars with high and low masses, but none at the intermediate degenerate mass limit to form VS stars also remains unexplained. Indeed, 1-2 Gyr old stars with $[\text{Fe}/\text{H}] \sim -0.3$ dex are very common in the LMC, although VS stars are only clearly seen in certain parts of the galaxy, which constitutes an unresolved mystery.

The authors would like to thank the CTIO staff for their kind hospitality during the observing run. A.E.P. greatly appreciates the opportunity provided by CTIO of spending

two months of his Gemini Fellowship at its Headquarters in La Serena, Chile. Support for this work was provided by the National Science Foundation through grant number GF-1003-98 from the Association of Universities for Research in Astronomy, Inc., under NSF Cooperative Agreement No. AST-8947990. Peter Stetson is also sincerely acknowledged for his help in the installation and execution of DAOPHOT and DAOMASTER. D.G. would like to acknowledge a very useful conversation with D. Alves who pointed out the importance of observing NGC 2209. We also thanks the referee for his valuable comments and suggestions. A.E.P. and J.J.C. acknowledge the Argentinian institutions CONICET and CONICOR for their partial support. J.F.C.S. Jr. also acknowledges the Brazilian institutions CNPq and FAPEMIG for their support.

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Fig. 1.— Schematic mosaic of the 21 fields observed in the north of the LMC. The number of VS stars in each field is also indicated. Note the strong concentration just north-east of the cluster SL 509. Fields with an asterisk have tilted RGC (see Section 3.1 for details).

Fig. 2.— Typical Washington T_1 vs. $C - T_1$ CMD for a selected field in the northern part of the LMC. Each field contains on average 12,000 stars.

Fig. 3.— Enlargement of the RGC region in the Washington T_1 vs. $C - T_1$ CMD for each selected LMC field. Field identification is also shown (see Table 1).

Fig. 4.— Composite Washington T_1 vs. $C - T_1$ CMD using all the measured stars in the selected LMC fields. The SL 388 and SL 509 cluster fields are also included (see Section 3.2 for details). Note that VRC and HB stars are also present (see Section 3.4 for details).

Fig. 5.— Relationship between the number of field VS stars and the number of RG box stars. Symbols represent selected LMC fields (\star), NGC 2209 field (\triangle), and previously published LMC cluster fields (\square) (see Sections 3.2 and 3.4 for details).

Fig. 6.— Washington T_1 vs. $C - T_1$ CMD for the NGC 2209 field, which is located $\sim 14^\circ$ away from the selected fields in the northern part of the LMC. A line following the direction of the reddening vector ($\Delta E(B - V) = 0.20$) is also shown.

Fig. 7.— Luminosity function for VS stars.

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Table 1. Selected fields

Name	RA (2000) (hh:mm:ss)	Dec. (2000) (°:′:″)	Cluster Name
Field 1	05:34:59.7	-63:43:08.4	OHSC 22
Field 2	05:33:05.7	-63:42:27.4	LW 238
Field 3	05:31:11.7	-63:40:45.5	OHSC 20
Field 4	05:28:16.5	-63:41:27.6	OHSC 17
Field 6	05:25:29.7	-63:39:48.6	
Field 7	05:23:35.7	-63:30:47.2	
Field 8	05:21:41.7	-63:30:47.2	
Field 9	05:18:12.4	-63:27:31.3	SL 354
Field 10	05:16:18.4	-63:25:09.5	
Field 11	05:16:18.4	-63:12:24.5	SL 345, SL 346
Field 12	05:20:06.4	-63:04:19.6	OHSC 10
Field 13	05:25:06.8	-63:06:44.6	SL 448, LW 209, KMHK 854
Field 14	05:31:25.7	-63:53:30.5	SL 540
Field 15	05:30:46.9	-64:06:15.5	SL 525
Field 18	05:30:37.4	-63:28:42.6	SL 515, SL 529
Field 19	05:30:47.5	-63:15:57.6	NGC 1997, LW 230
Field 20	05:30:03.2	-63:03:12.6	OHSC 18
Field 21	05:25:06.8	-63:18:54.7	
Field 22	05:24:27.4	-63:52:33.6	NGC 1942
Field 24	05:20:48.8	-64:03:56.9	SL 401
Field 25	05:18:54.8	-64:05:03.8	SL 372
NGC 2209	06:08:36.0	-73:54:00.0	

Table 2. Transformation coefficients

Date (UT)	a_1	a_2	a_3	b_1	b_2	b_3
Nov. 18, 1998	2.414	0.295	-0.047	2.164	0.077	-0.014
	± 0.021	± 0.013	± 0.005	± 0.020	± 0.013	± 0.005
Nov. 19, 1998	2.428	0.284	-0.048	2.134	0.102	-0.014
	± 0.031	± 0.019	± 0.007	± 0.019	± 0.013	± 0.005
Nov. 20, 1998	2.488	0.242	-0.058	2.123	0.091	-0.007
	± 0.030	± 0.022	± 0.006	± 0.025	± 0.019	± 0.004
Nov. 21, 1998	2.391	0.348	-0.084	2.115	0.106	0.004
	± 0.034	± 0.023	± 0.007	± 0.031	± 0.022	± 0.005
Nov. 22, 1998	2.352	0.358	-0.063	2.047	0.178	-0.016
	± 0.033	± 0.024	± 0.007	± 0.025	± 0.018	± 0.004
Nov. 23, 1998	2.517	0.222	-0.047	2.178	0.070	-0.011
	± 0.023	± 0.015	± 0.004	± 0.019	± 0.012	± 0.004

Table 3. Luminosity function for VS stars

T_1 (mag)	Number of stars
18.775	1094
18.825	957
18.875	949
18.925	771
18.975	815
19.025	791
19.075	771
19.125	798